Evaluation of a diode array for QA measurements on a helical tomotherapy unit


Department of Radiation Oncology, M. D. Anderson Cancer Center Orlando, Orlando, Florida

K. J. Ruchala and G. H. Olivera

TomoTherapy Inc., Madison, Wisconsin

(Received 23 May 2005; accepted for publication 1 September 2005; published 21 October 2005)

A helical tomotherapy system is used in our clinic to deliver intensity-modulated radiation therapy (IMRT) treatments. Since this machine is designed to deliver IMRT treatments, the traditional field flatness requirements are no longer applicable. This allows the unit to operate without a field flattening filter and consequently the 400 mm wide fan beam is highly inhomogeneous in intensity. The shape of this beam profile is mapped during machine commissioning and for quality assurance purposes the shape of the beam profile needs to be monitored. The use of a commercial diode array for quality assurance measurements is investigated. Central axis beam profiles were acquired at different depths using solid water built-up material. These profiles were compared with ion chamber scans taken in a water tank to test the accuracy of the diode array measurements. The sensitivity of the diode array to variations in the beam profile was checked. Over a seven week period, beam profiles were repeatedly measured. The observed variations are compared with those observed with an on-board beam profile monitor. The diode measurements were in agreement with the ion chamber scans. In the high dose, low gradient region the average ratio between the diode and ion chamber readings was 1.000 ± 0.005 (±1 standard deviation). In the penumbra region the agreement was poorer but all diodes passed the distance to agreement (DTA) requirement of 2 mm. The trend in the beam profile variations that was measured with the diode array device was in agreement with the on-board monitor. While the calculated amount of variation differs between the devices, both were sensitive to subtle variations in the beam profile. The diode array is a valuable tool to quickly and accurately monitor the beam profile on a helical tomotherapy unit. © 2005 American Association of Physicists in Medicine. [DOI: 10.1118/1.2089547]

Key words: tomotherapy, quality assurance, diode array

I. INTRODUCTION

A TomoTherapy™ Hi*Art II unit delivers radiation therapy plans using a helical tomotherapy technique. A linear accelerator is mounted on a ring gantry that continuously rotates while the patient is translated along the axis of gantry rotation during treatment delivery. The beam has a fan geometry and a 64 leaf binary collimator is used to subdivide this fan beam into beamlets. Intensity modulation is achieved by a temporal modulation of the collimator leaves.

The unit is designed for intensity modulated treatment delivery and therefore the traditional requirement of a flat radiation field across the treatment field does not exist anymore. The TomoTherapy Hi*Art unit takes advantage of this and a field flattening filter is omitted. The advantage of this design is a relatively high machine output and a radiation field that varies less in energy across the field.

During machine commissioning, the nonuniform beam profile is mapped using an ion chamber scan in a water tank. To calculate collimator leaf opening times, the relative output for each leaf’s off-axis location is determined from the beam profile and taken into account. It is therefore necessary to periodically monitor the shape of the beam profile and to verify its consistency. Water tank measurements are tedious on a monthly basis and the verification of nonuniform fields with film dosimetry requires the acquisition of a film calibration curve. The measurement of the beam profile with a commercially available two-dimensional (2-D) diode array was therefore investigated. Advantages are the immediate availability of the results and ease of use.

The diode array investigated was designed for use on a TomoTherapy unit and it is manufactured by Sun Nuclear Corp. of Melbourne, FL. This device, henceforth referred to as TomoDOSE™, was used for all test measurements reported. First, the TomoDOSE readings are compared with ion chamber scans in a water tank to test the diode array’s accuracy. Second, the sensitivity of the diode array to subtle changes in the beam profile was tested. To monitor the beam profile, TomoTherapy’s on-board detector array can also be used. Over the course of seven weeks, the monitoring of the beam profile via this on-board detector array was compared with repeated TomoDOSE measurements. Incidentally, a continuous change in the beam profile was observed during this period. These changes were subtle yet persistent and were used to diagnose deterioration of the x-ray target. Prior to this observation the x-ray target had been used for 18 months. The x-ray target was replaced at the end of the seven week observation period.
II. MATERIALS AND METHODS

A. The TomoDOSE array

The diode array contains 232 diodes that are arranged in a 530 mm by 100 mm rectangle. The rectangular field is designed to map the rectangular radiation field of the TomoTherapy unit, which has a maximum field size of 400 mm by 50 mm at the isocenter. Figure 1 shows the arrangement of the diodes in the device. Along the lateral axis, the diode spacing is 5 mm. Along the longitudinal axis the diode spacing varies with the off-axis distance, ranging from a 4 mm spacing on the central axis to an 8 mm spacing at the outer off-axis distances. This arrangement allows the simultaneous measurement of the lateral and longitudinal beam profile in the center of the radiation field and eight longitudinal beam profiles at off-axis distances of ±50, ±100, ±150, and ±190 mm. The diodes are radiation hardened N-type Si diodes and the device has an inherent build up of 9 mm equivalent of water. Each diode has an active area of 0.8 mm × 0.8 mm. The device was calibrated in a homogeneous radiation field that covered the complete diode array. A 6 MV photon field generated by a Varian 600 machine was used for this calibration. The TomoDOSE’s manufacturer’s calibration procedure was followed.

Prior to data acquisition, the array was leveled and a background measurement was acquired. The array was irradiated for 20 s in a 400 mm by 50 mm radiation field. With a 85 cm source-to-surface (SSD) setup, this irradiation time results in an absorbed dose of 2.7 Gy at a $d_{\text{max}}$ of 13 mm. Using additional solid water buildup material and a fixed SSD setup, the array was placed at depths of 15, 50, 100, 150, and 200 mm. These depths were chosen to enable a comparison with ion chamber scans in a water tank that were acquired at the same depths.

After acquisition, all data were mirrored about the central axis to enable a visual centering of the data. A lateral offset was introduced such that both field edges were an equal distance away from the central axis. This procedure corrects slight lateral offsets of the array with respect to the beam center. Typically these corrections were less than 2 mm. For a comparison with water tank scans, these centered data are used directly.

The centering procedure necessitates an interpolation of the diode data if variations in the beam profile between different TomoDOSE irradiations are to be monitored. Due to the centering correction for each TomoDOSE beam profile, the absolute spatial position of a given diode will be slightly different from one profile to another. The first profile was designated as the reference and for each subsequent profile measurement the reading for the reference diode position was determined by linear interpolation between neighboring diodes. The 5 mm diode spacing provides a sufficient spatial sampling frequency in the moderate profile intensity gradient to justify interpolation.

B. Ion chamber scans in water

An AISL Exradin ion chamber (Standard Imaging, Middleton, WI) was used to acquire beam profiles in a water tank. The chamber has a collecting volume of 0.056 cm$^3$ and an outside diameter of 6.25 mm. Lateral and longitudinal beam profiles were acquired at depths of 15, 50, 100, 150, and 200 mm.

C. On-board detector array

A xenon-filled array of ion chambers is mounted opposite the linear accelerator. During routine clinical operation this detector array is used for the acquisition of Megavoltage CT images (MVCT). The array has a 1.1 m radius of curvature while the source to detector distance is 1.42 m. Consequently, this array is not focused on the radiation source. The individual ion chambers are separated by tungsten septa that intercept the beam at different angles since the detector array is unfocused. This leads to a variation in the response of the ion chambers to the incident photon fluence. The raw detector readings therefore do not reflect the shape of the beam profile. However, a response change in individual ion chamber channels can be used to detect variations in the incident photon fluence and the array can be used to monitor changes in the beam profile. The on-board array is therefore heavily used for diagnostic purposes by TomoTherapy’s service engineers. At the time of commissioning, a standard beam profile is established using the on-board detector array. Subsequent measurements are then compared with this data for routine maintenance inspections.

III. RESULTS

A. Comparison to water tank ion chamber scans

The accuracy of the diode array’s measured beam profile is evaluated by a comparison with ion chamber scans in a water tank. Data for both lateral and longitudinal central axis scans were compared. Figures 2 and 3 show both sets of data. Within the high dose, low gradient area, the mean ratio
between the ion chamber and diode reading is $1.000 \pm 0.005$. In the penumbra region the distance to agreement (DTA) criterion was used to evaluated the device. In the penumbra region of the longitudinal scans, all diode readings fulfilled the 1 mm DTA criterion. In the penumbra region of the lateral scans, all diodes were within 2 mm of the DTA. The normalized diode reading differed from the ion chamber scan by up to 60% in the high gradient region. Outside the pri-
mary beam, in the low dose, low gradient area of the longi-
tudinal profiles, the diode array readings tend to be higher
than the ion chamber readings. This effect increases with
depth and a maximum difference of 14% is observed in the
longitudinal scan measured at a depth of 200 mm.

B. Comparison to TomoTherapy's on-board data

During a seven week time period, lateral beam profiles
were measured with the TomoDOSE array. To quantify any
variations in the beam profile, a TomoDOSE measurement

Fig. 3. A comparison of longitudinal beam profile measurements at various water depths. The TomoDOSE profiles are compared with the ion chamber scans in water. All scans are normalized to unity on the central axis reading. In (f) all data are shown with the reading on the central axis normalized to the central axis reading at 15 mm depth. The field size was 50 mm by 400 mm.
that was obtained seven months prior to the seven week observation period was used as the reference. All TomoDOSE measurements were measured at a SSD of 85 cm and a solid water depth of 15 mm.

Figure 4 reveals that the beam profile changed with respect to the reference measurement. For clarity, the figure only shows the reference data and profiles measured in the fourth and seventh weeks. Figure 5 is a close-up view of the beam profile edge and shows all data obtained during the seven week interval. These data were analyzed for changes in the beam profiles relative to the reference data. Each scan was normalized to unity on the central axis. To monitor the beam profile the ratio of each measurement to the reference data was calculated. The analysis of the TomoDOSE data is shown in Fig. 6. The continuous decrease of the off-axis beam ratio with time is more readily apparent when plotted as the ratio of the reference profile. The change in the beam profile is accelerated toward the end of the observation period.

The TomoTherapy on-board detector array can also be used to monitor variations in the lateral beam profile. For the same time period that the diode array was used to monitor the beam profiles, data from the on-board detector array are available. The data were acquired on the same days that the TomoDOSE data were taken. An on-board detector reading that was obtained eight months earlier was used as the reference. Figure 7 shows changes in the beam profile according to the on-board detector system. These data also show a
decrease in the off-axis beam ratio with time. The trend in the data, i.e., a continuous decrease in the off-axis ratio with time, is evident in both sets of data. The absolute decrease is larger for the on-board data.

IV. DISCUSSION

The comparison with water tank ion chamber data shows that the beam profiles measured with the TomoDOSE diode array are accurate. Within the radiation field, the diode readings deviate from the water tank scans with a standard deviation of about 0.5%. A similar good agreement in the high dose, low gradient region between water tank ion chamber scans and diode arrays (MapCheck™ and PROFILER™, both by Sun Nuclear) has been reported by others. In the penumbra region, the diode measurements had a much larger disagreement but fulfilled reasonable DTA criteria (1 mm for the longitudinal scans and 2 mm for the lateral scans). In a similar comparison, Létourneau et al. report (i) good agreement between film and diode array measurements in the beam penumbra and (ii) a 1.5 mm DTA discrepancy between their film and ion chamber data. Zhu et al. reported a maximum of 2 mm DTA shift for diode measurements in the penumbra region. Our results are in agreement with those reports. The diodes are physically smaller than the ion chamber and are subject to a lesser degree of volumetric averaging. The reason for the difference between the diode and the ion chamber readings in the low dose, low gradient reading that was observed in the longitudinal scans is unclear. Other
workers have reported an excellent linearly in-diode reading of the devices down to doses as low as 1 cGy.\(^3\)–\(^5\) The relatively high atomic number of the diode could possibly contribute to an over-response outside of the field where the dose is due to low-energy scatter radiation.

While the requirement of a flat beam profile for regular linear accelerators does not exist anymore for a machine that is designed for IMRT treatment delivery, the requirement of a consistent beam profile over time remains unchanged. In the AAPM Task Group Report 40, a monthly check of the beam flatness consistency is recommended and a tolerance level of 2% is given.\(^6\) This recommendation can be used to establish guidelines for checking the beam profiles on a TomoTherapy unit. While the on-board detector system can be used to detect variations in the beam profile, this data is at the moment not easily accessible to the clinical physicist. An independent device that is accurate and fairly easy to use is of obvious value. In our clinic, we have used the TomoDOSE array repeatedly for a second check of the beam profile consistency after machine component replacement. In addition, we have started to use the device for monthly measurements of the beam profiles.

Both the on-board detector system and the TomoDOSE array showed that the lateral beam profile changed continuously over this particular course of seven weeks. However, the amount of variation is different according to the two systems, with the on-board detector indicating a larger degree of variation. It must be kept in mind that these two arrays measure different quantities. While the diode array measures the dose at a water-equivalent depth of 15 mm near the isocenter, the on-board detector array signal is proportional to the fluence incident onto the individual detector element at a distance of about 60 cm beyond the isocenter. Changes in the fluence distribution may affect the two detector arrays differently. The demonstrated accuracy of the TomoDOSE measurements supports these results over the on-board detector array results for the quantification of beam profile changes. Both methods are clearly sensitive to variations in the beam profile.

The ability to detect changes in the beam fluence is useful beyond the obvious necessity of monitoring the beam profile. In our particular case, the decrease of the off-axis beam ratio could be used to diagnose a deterioration in the x-ray target and to trigger preventive maintenance. The tungsten target is in direct contact with the cooling water and this leads to a relatively rapid deterioration of the target. A decrease in the off-axis beam ratio can be used to diagnose a thinning of the target. The target was replaced prior to the presumed failure. Subsequent monthly TomoDose and on-board detector array measurements have indicated a stable beam profile.

V. CONCLUSION

The TomoDOSE array can be used to accurately measure the beam profiles in a helical tomotherapy unit. The ease of use and the immediate availability of the results make this device ideal for routine QA measurements.

\(^1\)Corresponding author. Electronic mail: Katja.Langen@orhs.org


